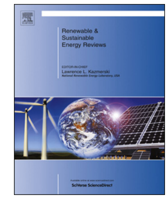
Renewable and Sustainable Energy Reviews 26 (2013) 286–293

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



A review on solar assisted heat pump systems in Singapore

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ARTICLE INFO

Article history:
Received 24 March 2011
Received in revised form
1 May 2013
Accepted 13 May 2013
Available online 21 June 2013

Keywords:
Solar energy
Ambient energy
Heat pump
Integrated system
Heating
Cooling and drying

ABSTRACT

A solar assisted heat pump is used for different applications, such as, water heating, drying and air conditioning. The unglazed evaporator-collector enables to absorb both solar energy and ambient energy due to low operating temperature. Three different systems are described: solar assisted heat pump system for hot water using an unglazed evaporator collector; solar assisted heat pump for hot water and drying, where evaporator collector and air collector are used; an integrated solar heat pump system making use of solar and ambient energy, and air-con waste heat. Unlike conventional collector, evaporator collector was found to have higher efficiency, 80% to 90%, and the coefficient of performance attained a value as high as 8.0. The integrated system leads to a reduction of global warming, as it uses solar energy, ambient energy and air-con waste heat.

Contents

1. Introduction

The growing demand for energy resources, escalating fossil fuel prices and global warming have created a new dimension to look for sustainable energy resources with minimum impact on the environment. In an effort to make rational use of energy resources, solar energy, a clean, environment friendly and sustainable resource, can play an important role [1]. There is significant utilization of solar energy, particularly in the areas where low temperature (temperature less than 100 °C) are involved e.g. drying in agricultural sectors [2].

A combination of solar energy and heat pump can improve the quality of the energy available and shows potential for different

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.05.032

applications [3]. The evaporator-collector used in such system can absorb both solar and ambient energy [4]. Abou-Ziyan [5] conducted series of experiments with R 22 and 134a to identify appropriate refrigerant for solar applications. Hawlader et al. [6], Lu et al. [7] and Chyng [8] used solar assisted heat pump (SAHP) to produce hot water. Due to low operating temperature, the evaporator-collector absorbed both solar energy and ambient energy. The coefficient of performance (COP) of the system reached as high as 9 for refrigerant R134a. Huang and Lee [9] studied the long term performance of solar assisted heat pump water heater. Grossman [10] conducted experiments with a solar heat pump system to provide cooling, dehumidification and air-conditioning. Hawlader et al. [11] conducted series of experiments on a solar assisted heat pump system (SAHPS) for water heating and drying. They have also done research in the regime of heat pump desalination with utilizing only solar energy [12] as well as utilizing both solar heat and air-con waste heat [13]. On top of it, an integrated solar assisted heat pump system for air-conditioning, water heating and drying was proposed by Hawlader et al. [14]. This system uses solar energy, ambient energy and air-con waste heat to provide hot water and drying. This paper includes some of the results obtained from several solar assisted heat pump systems tested under the meteorological conditions of Singapore for different applications.

2. Background of SAHP systems

A number of investigations have been conducted by researchers in the design, modeling and testing of solar-assisted heat pump systems (SAHPS) [15–22] to evaluate its performance and technical feasibility for various applications, such as water heating, and space heating and cooling. Morgan [15] investigated a direct expansion solar assisted heat pump using R-11. The heat pump was specially designed for use in a tropical climate, where the normal ambient temperature of the day above 25 °C permitted the operation of evaporator at a high temperature, 15 °C to 50 °C, depending to the solar input. His result demonstrates the feasibility of utilizing the system to heat water up to 90 °C with a COP varying from 2.5 to 3.5.

Krakow et al. [16] investigated a direct expansion solar assisted heat pump system using collector plates fitted with fins for space heating. They asserted that solar source heat pump systems with glazed solar collector are preferable to systems with unglazed solar collectors for cold climates. They also reported that systems with unglazed solar collectors might be advantageous for warm climates. A field-test plant of the direct expansion solar assisted heat pump system for heating and hot water supply was set up for practical use by Fijita [17]. The system had an outdoor coil and a covered collector, which included a refrigerant cycle. Two evaporators were connected in series, and heat transfer from the evaporator was carried out through forced convection on rainy and cloudy days. The system was used for floor heating and hot water supply and exhibited an improve performance with a COP of 5–8 in the solar mode and 2–3 in the air mode.

Hino [18] developed a direct expansion solar assisted heat pump for heating and cooling. The outdoor panel operated as an air source evaporator as well as the solar collector in the heating mode, and operated as a condenser and dissipated heat to make ice in the cooling mode. The outdoor panel was made of extruded aluminum and fins were connected at the back of panel for collection of heat both on sunny days and cloudy days. The heat storage coil unit was used to make hot water in winter and ice in summer. Tleimat and Howe [19] developed a solar-assisted heat pump system for heating and cooling of residences. The proposed system makes use of a conventional air-conditioner unit which would be modified by fitting control to reverse the flow of refrigerant for the heating mode and by changing the outdoor heat exchanger from refrigerant-to-air to refrigerant-to-water. In addition, it included a solar collector and two insulated water storage tanks. It was concluded that the solar-assisted heat-pump system with current fuel prices can provide immediate economic benefit over the all-electric home. Collector efficiency, heat pump COP, system COP, and storage efficiency were found 70%, 4.5%, 4% and 60%, respectively, for space heating presented by Omer et al.[20].

Svard et al.[21] described a general design procedure for solar assisted heat pump systems for space and process water heating. Their procedure accounts for the variable efficiency and rate of energy delivery by the heat pump. They reported that the capacity of the heat pump relative to the load requirement significantly affects the overall system performance. Hawlader and Zakaria [22] performed analytical and experimental studies on a solar assisted heat pump system, where unglazed flat plate solar collectors acted as an evaporator for the R-134a. They showed that the system is influenced significantly by collector area, speed of compressor, solar irradiation and storage volume.

Rice drying system using a solar assisted heat pump was developed by Best et al. [23,24]. They dried 44.8 kg of rice from 25.5% (db) initial moisture content to 11.45% (db) final moisture content, where average temperature was 30.8 °C, within 4.9 h with heat pump, rejecting the hot and humid air to the ambient. The measured energy consumption, COP, and specific moisture content were 969.5 kJ/kg, 5.3, and 3.5 kg/kW h, respectively. Manuel et al. [25] developed a simulation model of drying system assisted by vapor compression heat pump. The heat pump was used to preheat the air stream before it enters the drying chamber. Results have shown that a considerable reduction in energy consumption can be obtained with the use of a heat pump. They presented two major conclusions. First, higher mass flow rates imply lower specific power consumption. Second, the heat pump proved to be more efficient than conventional heating system at any operating condition.

Minduan [26] proposed a solar assisted heat-pump system to supply heat for industrial processes in the range 100–130 °C. He showed that the system was economically superior to electrical heating and solar-only systems, and was competitive with fuel burning systems. Frank et al. [27] studied the economic performance of a solar system, air-to-air heat pumps, and several solar-assisted heat pump systems for residential heating. They concluded that the air-to-air heat pump was preferred when there is no price differential during peak/off-peak period. Solar system was preferred when the electricity price was doubled.

McDoom et al. [28] investigated on the moisture content reduction of coconut and cocoa using a scaled-down dryer of the type found on coconut estates in Trinildad. They stated an energy saving of 29% to 31% was realized by recirculating the hot air and varying the degree of venting. In addition, this saving could also be effected on the estates with suitable modification of the dryers used there.

Water heating and drying are energy intensive processes and, in order to make the system energy efficient, it is necessary to have a better understanding of the problem. In conventional systems, waste heat from air-con space cooling is vented to the atmosphere, which results in thermal loss. This energy can be recovered with the use of a heat pump system. Solar energy provides low grade heat. The incorporation of a solar heating system to the heat pump, thus, further improves on the efficiency of the overall process.

3. Development of SAHP systems

Before presenting the integrated solar system for air conditioning, water heating and drying, a brief discussion of the other

systems considered by the author that led to this development will be presented. The author started with the development of solar assisted water heater using heat pump [6] in 2001. This was followed by the development of solar assisted heat pump system for water heating and drying [11]. These systems use solar energy as well as ambient energy, as the solar evaporator-collector temperature is lower than the ambient temperature during most of the operating time. Finally, the SAHPS for air conditioning, water heating and drying was designed, fabricated and installed with extensive instrumentation to evaluate its performance. Experiments were conducted under the meteorological conditions of Singapore on all the systems described here.

3.1. SAHPS for water heating

A SAHPS for water heating was designed, as shown in Fig. 1, to operate under the meteorological conditions of Singapore [6]. Two serpentine solar collectors, which act as an evaporator, were connected in series. A copper tube of 9.52 mm diameter was soldered at the back of the absorber plate. Adequate insulations were provided at the back of the collector but no glass cover was used on the top surface i.e. unglazed collector. There is a bypass line from the exit of the first collector-evaporator to the exit of second collector-evaporator, which remains closed or open depending on the solar irradiation and speed of the compressor. The ambient air also acts as a heat source depending on the operating temperature of the evaporator-collector.

A thermostatic expansion valve is used for the system, which maintains constant superheat at the inlet of the compressor by regulating the mass flow rate of refrigerant with the help of a feeler bulb [29]. An open type-reciprocating compressor is used for the system, which is directly coupled to a three-phase induction motor. A frequency inverter is used to control the speed of the motor. A pressure switch is used to protect the compressor/motor from overloading. The condenser is installed inside a tank made of fibreglass to store water for heating purposes. The tank was insulated to prevent heat loss from the hot water to the surroundings.

The temperature and pressure of the refrigerant were measured at various locations of the system. The ambient temperatures, incident solar radiation, plate temperature on each solar collector at several locations were measured. Pressures were measured with pressure transducers. A pyranometer was mounted near the collector to measure the instantaneous solar radiation. The flow rate of refrigerant was also measured by means of magnetic flow meter. The power consumption of the system was measured by a wattmeter. For the acquisition of the data, an automatic data logging system was used. All quantities were monitored continuously and stored at 5 min interval in the data logger.

3.2. SAHP for water heating and drying

A solar assisted heat pump dryer and water heater has been designed and fabricated, as shown in Fig. 2. The system was located on the rooftop of a four-storey building at the National University of Singapore. The setup consisted of two distinct flow paths: air and refrigerant.

3.2.1. Air flow path

The air flow path, represented by the dotted line in Fig. 2, dealt with the air, which was maintained at a desired condition at the inlet to the dryer. The various components in the air path were: solar air collector, air cooled condenser, auxiliary heater, blower, dryer unit, dehumidifier, temperature controller and dampers. The drying chamber contained multiple numbers of nylon mesh trays to hold the drying material and expose it to the airflow. A well-designed duct system delivered the air to the desired locations. The duct was thermally insulated to have an adiabatic environment. The incoming air was heated by the solar air collector, and then flowed over the condenser coil, where it was heated further by the heat released by the condensing refrigerant. The magnitude of the desired dryer inlet temperature and the meteorological conditions determined the amount of auxiliary energy required for a particular application. The air at the pre-set drying condition entered the dryer inlet and performed drying. The air leaving the dryer was cooled and dehumidified, to get rid of the moisture absorbed in the dryer, thereby, a rejection of sensible and latent heat occurred at the de-humidifier. Subsequently, this heat was available at the air-cooled condenser for the re-processing of the air for the next cycle. The cycle was repeated until the required moisture level of the drying material was attained.

A vane type anemometer was used to measure the flow rate and velocity of the air. The pressure and temperature at different locations of the refrigerant path were measured using pressure transducers and thermocouple probe, respectively. The flow rate of refrigerant was measured with the help of a magnetic flow meter. The power consumption of the system was measured by a wattmeter. Finally, the data acquisition system includes four data loggers, comprising 20 channels each.

3.2.2. Refrigerant flow path

The refrigerant path, represented by the continuous line in Fig. 2, consisted of a vapour compression heat pump unit. A dehumidifier, an evaporator-collector, an open type reciprocating compressor, evaporator pressure regulators, expansion valves, condenser tank, and a fan coil unit were the components of the heat pump. The dehumidifier and evaporator-collector were connected in parallel with individual expansion valves, as shown in

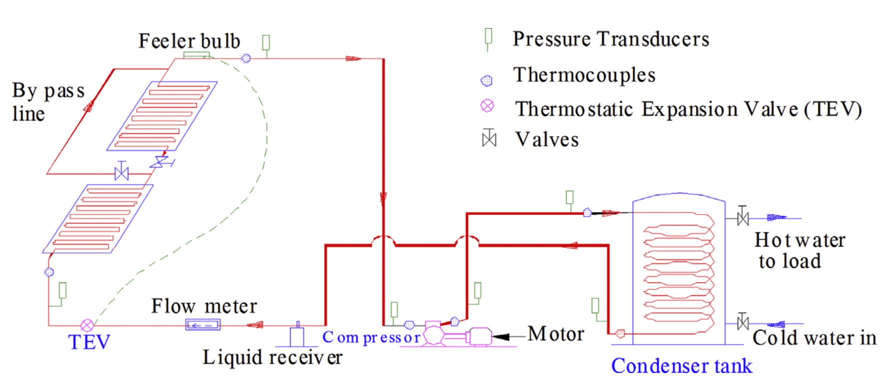

Fig. 1. Schematic diagram of a SAHP water heating system [6].

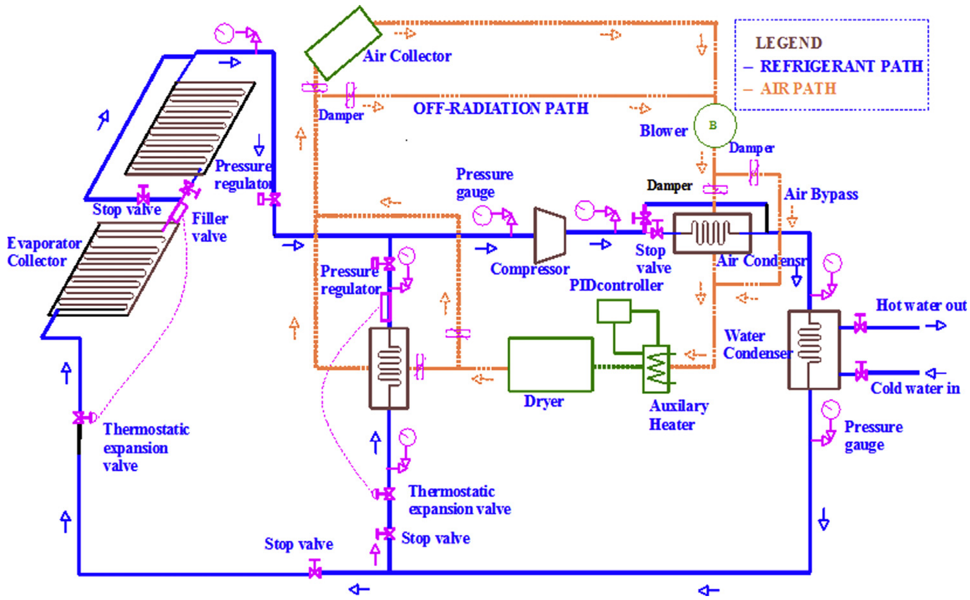

Fig. 2. Schematic diagram of SAHP system for drying and water heating [30].

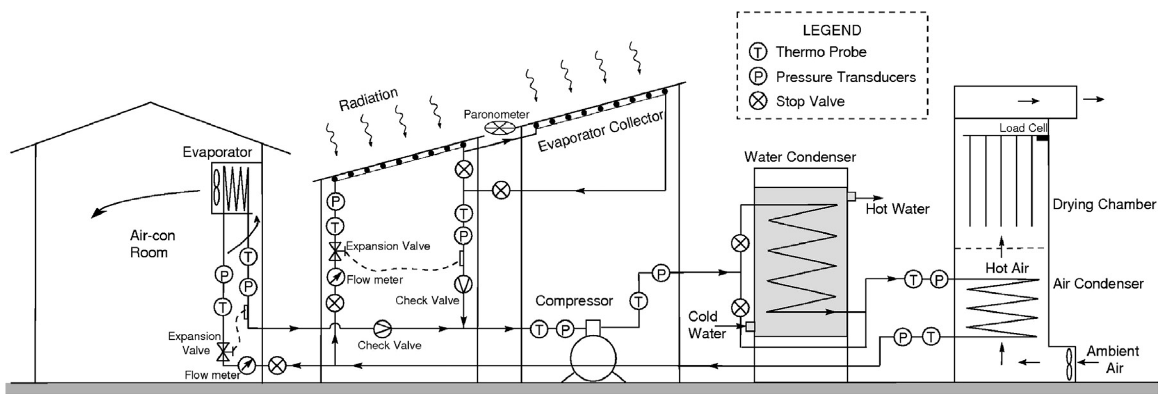

Fig. 3. Schematic diagram of an integrated solar heat-pump system [31].

Fig. 2. The refrigerant coming out of the air-cooled condenser passed through a coil immersed in a tank and heated the water in the tank to ensure complete condensation. The refrigerant used in the system was R134a, which was considered environment friendly. The experiment consisted of a series of drying test involving food grains and subsequent analysis of the drying characteristics as well as the system efficiency parameters. The principal system performance indices considered for analyses were: coefficient of performance (COP) and solar fraction (SF) of the system. The system was in a closed loop arrangement and the drying potential of the air was restored in each cycle through cooling and dehumidification of the air in the dehumidifier.

3.3. Integrated SAHP system

An integrated solar heat pump system for air-conditioning, water heating and drying was designed and built, as shown in Fig. 3. The various components of the system are: evaporator-collector, evaporator, variable speed reciprocating compressor, air-cooled and water-cooled condensers, drying chamber, blower and other control devices. The evaporator-collector was made of a copper absorber plate coated with black paint. Underneath the absorber plate, serpentine copper tubes of 9 mm diameter were brazed to enable the refrigerant to flow. The evaporator-collector and evaporator were connected in parallel with individual expansion valves. The air-cooled and water cooled condensers were connected in series, as shown in Fig. 3. Liquid entered the evaporator-collector, where flashing occurred due to pressure reduction and further heated by incident solar radiation or/and heat from the ambient air. The superheated refrigerant vapour from the evaporator-collector and the evaporator mixed and entered the suction side of the compressor. The high pressure and temperature refrigerant vapour from the compressor outlet first entered the coil immersed in the water of the condenser tank and then passed through the air-cooled condenser. The heat of condensation from the superheated refrigerant vapour was recovered both in air and water-cooled condensers, which otherwise would have been wasted in normal circumstances. The energy recovered in the water-cooled condenser heated the water, whereas, the energy released in air-cooled condenser heated the air for drying. The air-cooled condenser also ensured complete condensation of the refrigerant vapour with sub-cooling. The drying chamber contained drying material hung vertically to have good exposure to the incoming hot air from the air-cooled condenser. The hot and humid air at the drying chamber outlet was vented out. The sub-cooled liquid refrigerant re-entered the evaporators from the thermostatic expansion valves and the cycle was repeated. R134a was used as the refrigerant due to its better thermodynamic performance [5].

A well-equipped instrumentation system was deployed to measure various properties of the system, such as, the temperature, pressure, and the loss of moisture from the materials. For the

measurement of temperature at different locations of the air path, T-type thermocouples were used. An Eppley pyranometer was mounted near the evaporator-collector to measure the instantaneous solar radiation. The moisture measurement for the drying process was carried out with the help of a precision compression load-cell. The pressure and temperature at different locations of the refrigerant path were measured using pressure transducers and thermocouple probes, respectively. The flow rates of refrigerant through evaporators were measured with the help of two magnetic flow-meters. The power consumption of the system was measured by a wattmeter. All the above data were recorded using a data acquisition system comprising two data-loggers of 20 channels each.

4. Results and discussion

During the development of the solar assisted heat pump systems for different applications, extensive analyses were carried out to evaluate performance. The experiments were done under of the meteorological condition of Singapore. The climatic condition of Singapore is characterized by relatively uniform temperature, high humidity and abundant rainfall [32,33]. This is due to the island's close proximity to the equator and its maritime exposure. Hawlader et al. [34] developed a model for Singapore climate which was utilized for analysis. This section includes some typical results obtained under different operating conditions.

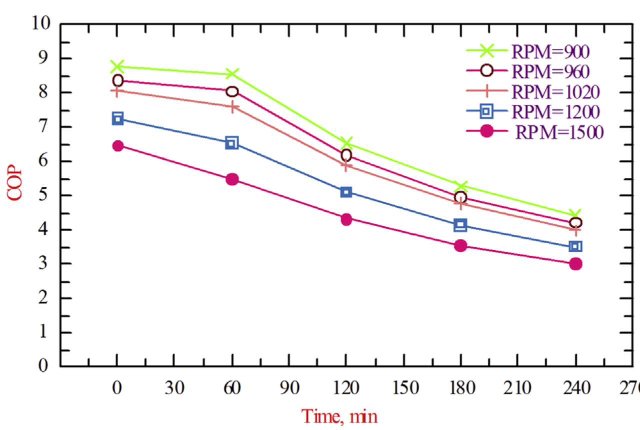

Fig. 4. Variation of COP with time for different speed of the compressor (solar radiation 600 W/m^2) [6].

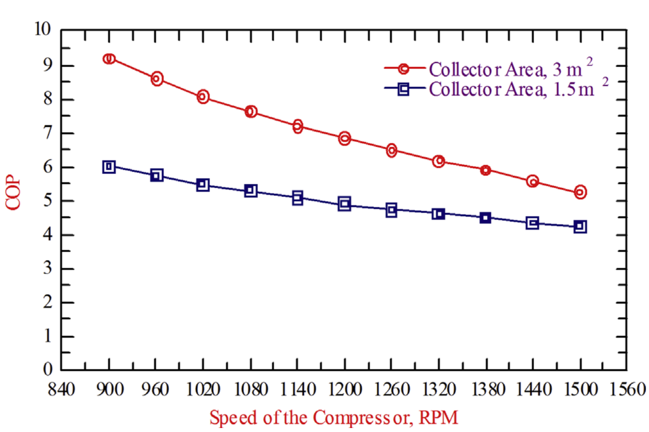

Fig. 5. Effect of compressor speed on COP with collector area as a parameter [6].

4.1. SAHPS for water heating

For this system, if the speed of the compressor was higher, mass flow rate of refrigerant through the collector-evaporator was also higher, which resulted in higher compressor work and lower COP, as shown in Fig. 4. Fig. 5 shows the variation of COP as a function of speed of the compressor with collector area as a parameter. For a particular speed of the compressor, if the collector area is smaller, refrigerant evaporates in the collector-evaporator at a lower temperature resulting in an increase in compressor work leading to a lower COP.

In Fig. 6, the predicted and experimental values of water temperature were plotted as a function of time. Here, compressor was operated at 1080 rpm and the ambient temperature varied

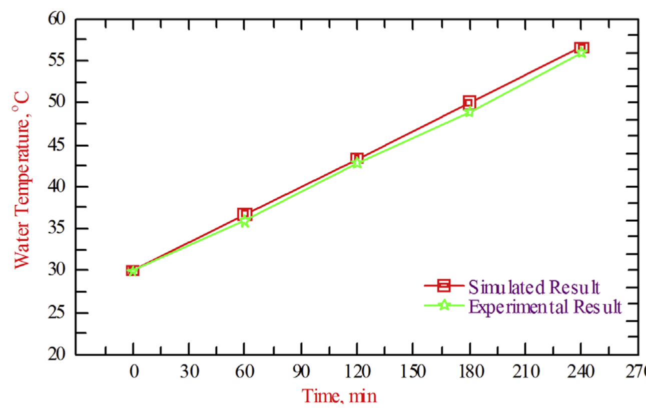

Fig. 6. Predicted and experimental temperature of water [6].

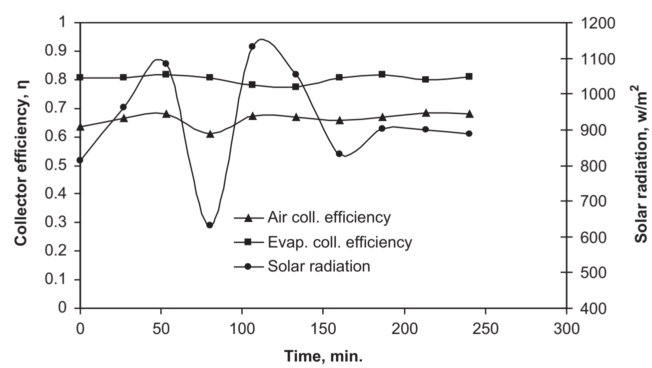

Fig. 7. Variations of collector efficiencies and irradiation with time.

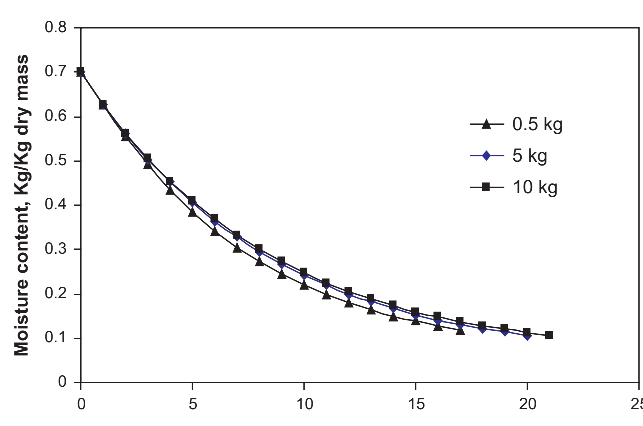

Fig. 8. Variation of moisture content with time for different samples [30].

between 28 °C and 36 °C. The predicted water temperature deviated no more than 0.9 °C from the experimental values of water temperature during the course of the experiment.

4.2. SAHP for water heating and drying

Fig. 7 shows the comparison of experimental efficiencies for evaporator and air collectors. As seen from the figure, the evaporator collector efficiencies were always higher than the air collector efficiencies. This could be attributed to the better thermodynamic characteristics of the evaporator-collector working fluid and the poor thermal properties of the air in the air collector. The figure shows a maximum evaporator-collector efficiency of 0.82 against a maximum air collector efficiency of 0.7. The higher efficiency of the unglazed evaporator-collector may be attributed to the lower operating temperature. Instead of heat losses, there is a heat gain from the surroundings. Also, a significant improvement in the air collector efficiency has been found due to lower operating temperature of the collector resulting from cooling and dehumidification of air in the dehumidifier. As seen from Fig. 7, the collectors are very sensitive to instantaneous solar radiation. Due to this, when the solar irradiation fluctuates, the collector operating temperature also fluctuates for a constant flow rate of the working fluid, leading to a corresponding change in the collector efficiency.

Fig. 8 illustrates how the moisture content variation is affected with a change in sample size of the material. The initial moisture content of the beans was set at 0.70 kg water per kg of dry beans. As expected, time taken to reach particular moisture content from the initial moisture content decreases with the increase in the weight.

Fig. 9 shows the variation of solar irradiation and temperature of water in the condenser tank along with ambient temperature. Both the predicted and experimental temperatures are shown in the figure. The water temperature steadily increases with time and solar irradiation. The compressor speed was set at 1800 rpm. As seen from the figure, the water temperature in the condenser tank increases regardless of the solar irradiation. This is due to the constant heat rejection in the condenser tank. Also, it is evident from the figure, as the solar irradiation decreases; the rate of increase in temperature of water also decreases. A maximum predicted water temperature of 54 °C, as observed from the figure, is obtained against an experimental maximum of 50 °C.

Fig. 10 shows the predicted and experimental COP, when the drying temperature was 55 °C with an air mass flow rate of 0.06 kg/s. A predicted COP of 7.0 and the corresponding experimental value of 6.45 were obtained under this condition. As seen from the figure, the higher COP values lied in the time region where the higher radiation occurred, suggesting that the COP increases with increase in solar irradiation. As the solar radiation increases, the evaporator-collector operating temperature increases resulting in lower temperature lift between the evaporator and condenser. The speed of the compressor was set at 1800 rpm.

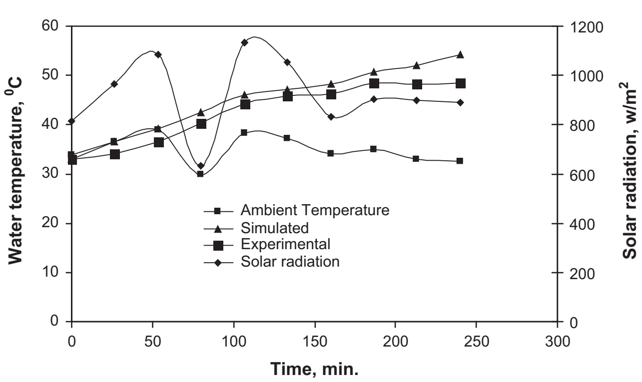

Fig. 9. Variation of water temperature with time (no load condition) [30].

4.3. Integrated SAHP system

Fig. 11 shows the change in refrigerant temperature at inlet and outlet of water-cooled condenser and water temperature in the tank with time. The temperature of 400 l of water in the tank increased in a steady manner and reached about 60 °C in nearly two and half hours.

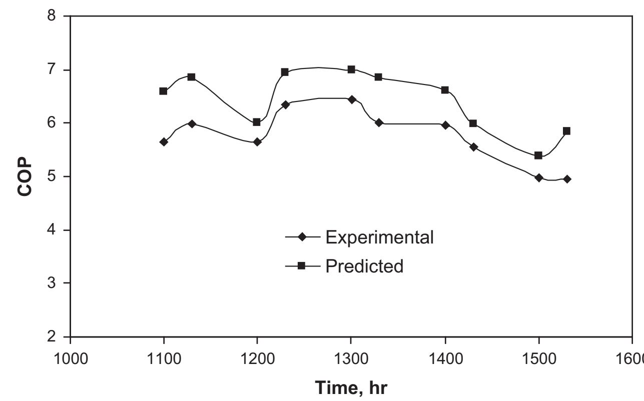

Fig. 10. Comparison between predicted and experimental COP [30].

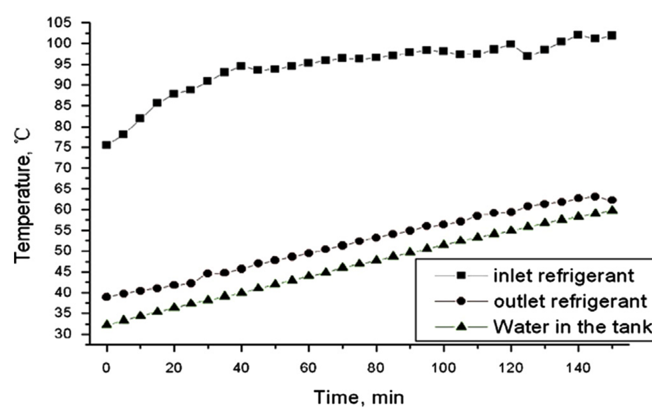

Fig. 11. Variation of water and refrigerant temperatures in water tank with time [31].

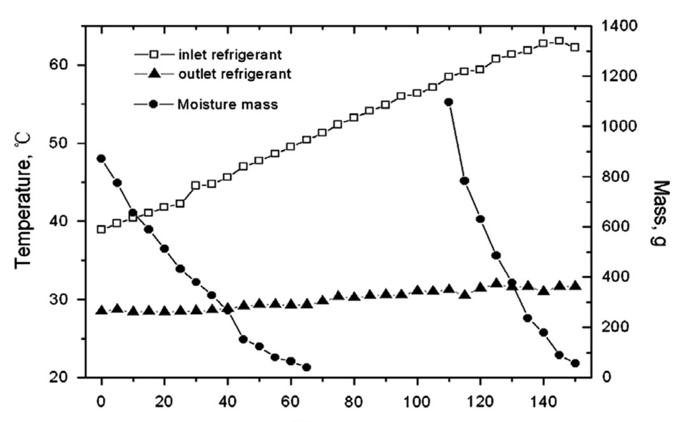

Fig. 12. Variation of temperatures and moisture contents with time [31].

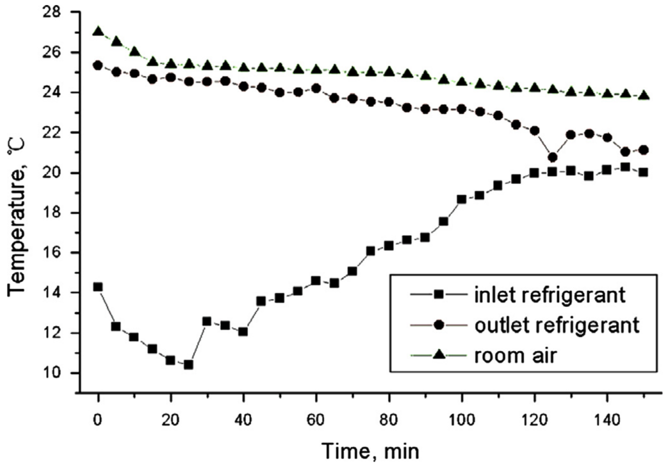

Fig. 13. Variation of temperature of air-conditioned room with time [31].

The drying effect is shown in Fig. 12, during the initial period, for lower water temperature in the tank, the drying was rather slow. This is due to the fact that significant amount of heat is utilized for heating the water in the tank. As the time elapsed, most of the refrigerant heat was used for heating the drying air due to the higher refrigerant temperature at the air-cooled condenser inlet. The higher refrigerant temperature was as a result of less heat transfer at the water cooled condenser, as it already reached a higher level of temperature.

Fig. 13 shows the change in room and refrigerant inlet and outlet temperature with time. As seen from the figure, the room temperature stabilizes with time. The difference in refrigerant inlet and outlet temperature with time was higher during the initial period and the difference got narrowed, as the room temperature stabilized.

5. SAHP performance around the globe

Research on SAHP system is not concentrated in few countries, rather researcher throughout the world have looked into it. They have designed and developed SAHP for their metrological conditions and analyzed the performance. Chaturvedi et al. [35] and Aziz et al. [36] developed a variable capacity direct expansion SAHPS in Virginia state, USA, which was used for domestic hot water application. This system employed a bare solar collector, which also acted as the evaporator of the system. Their experimental results indicated that the coefficient of performance of the system was 2.5 to 4.0 and concluded it can be improved significantly by lowering the compressor speed as ambient temperature rises from winter to summer.

In Romania, Badescu [37–39] studied on model of a thermal energy storage device integrated into a SAHPS for space heating and performed first law (energy) and second law (exergy) analysis of this system. He found that both the heat pump COP and exergy efficiency decreased when increasing the thermal energy storage unit length. Also, the monthly thermal energy stored by this unit and the monthly energy necessary to drive the heat pump compressor increased by increasing this unit length. Besides this, his preliminary results indicated that the photovoltaic array could provide all the energy required by the heat pump compress or, if an appropriate electrical energy storage system would be provided.

Kaygusuz [40–42] investigated the performance of a combined solar heat pump system with energy storage in encapsulated phase change material (PCM) packing for residential heating in the cold climate of Trabzon, Turkey. An experimental set-up was constructed. The experimental results were obtained from November to May during the heating season for two heating systems. The concluded for the Trabzon area the optimum solar collector are is 30 m^2 and storage volume is 1.5 m^3. Axaopoulos et al. [43] performed an experimental comparison of a SAHPS with a conventional thermosyphon solar system in Athens, Greece. Their experimental studies were monitored from 1993 to 1997 during summer and winter time periods. They reached the following experimental result from the operation of the SAHPS: COP is above 3 and water storage tank mean temperature reaches to 50 °C.

In Asia, Kuang et al. [44] investigated an experimental study on SAHP performance in the meteorological condition of Qingdao, China and concluded that the thermal storage tank was an important component in solar heating systems, which could modulate the mismatch between solar radiation and the heating load. In this system, the tank temperature was so close to ambient air temperature that its heat loss to the surroundings was very low. The maximum efficiency and COP they found was 67.2% and 2.55%, respectively. An Integral-Type Solar-Assisted Heat Pump (ISAHP) was developed by Huang and Chyng [8,9,45,46] in Taipei, Taiwan. Their ISAHP experimental system consisted of a Rankine refrigeration cycle and a thermosyphon loop that were integrated together to form a package heater. Both solar and ambient air energies were absorbed at the collector/evaporator and pumped to the storage tank via a Rankine refrigeration cycle and a thermosyphon heat exchanger. A 105-l ISAHP using a bare collector and a small R134a reciprocating-type compressor with rated input power 250 W was built and tested in the study. The COP values for the ISAHP built in the study were in the range 2.5–3.7 depending on the water temperatures. The highest COP value in the tests was 3.83 [45].

6. Conclusions

In an effort to develop an integrated solar heat pump system for multiple applications, the author started with a system for hot water only and evaluated the performance under meteorological conditions of Singapore using an evaporator collector. This was followed by a solar heat pump system for hot water and drying application, where evaporator and air collectors were used. This system used solar and ambient energy. The integrated multi-task solar heat pump system used solar and ambient energy, and air con waste heat providing space cooling, water heating and drying. The efficiency of the unglazed evaporator collector was found much higher than the air collector. The integrated system can be operated under single or multi-mode operations using either solar energy or ambient energy or waste heat. The COP of the system can be as high as 8.

Acknowledgements

The financial support for the experimental set-up was provided by the Department of Mechanical Engineering, National University of Singapore (NUS), Singapore. Authors would like to express their sincere appreciation for the NUS help.

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